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SUPERCONDUCTING MAGNET SYSTEM FOR A 750 GeV MUON SPECTROMETER*

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A spectrometer to measure deep inelastic muon scattering needs a uniform magnetic field, in an unobstructed space of 0.8 x 0.8 x 60 m, of 2 T vertical and transverse to the long direction. Outside the field space is an iron shield used for identifying and counting of muons, for reduction of stray flux, for improving field homogeneity and also for containment of magnetic forces. The magnet is composed of 6 m long units. Each unit is assembled by stacking 44 largely identical subunits. Each subunit is wound as a flat pancake on a window frame 1.7 x 6 m and bent into the required saddle shape. Cooling is by circulating two-phase helium through copper pipes attached to the subunits; heat transport within windings is through solid contact. Operating current, at 2 kA, is below the full stability limit. Half the magnetic forces are contained by cold tension struts connecting the two sides of the coil at top and bottom, the other half by supports between the center of the windings and the warm iron shield.

I. Introduction

Purpose and specifications. The proposed spectrometer is to be used for measurement of momenta of incident and scattered muons and angles between them.[1] The long target, 5 cm x 5 cm x 50 m of beryllium, liquid hydrogen or deuterium, requires a long spectrometer field. The aspect ratio can be small because, due to high energies, scattering angles and curvature of particle tracks are small. Particle tracks are recorded with time projection chambers (TPC) located in the air gap every 0.8 m in the long direction. The TPC need fields of high homogeneity ($\pm$ 2%) over their volume; their precision is such that a 2 T field is sufficient. The iron yoke is needed primarily as a muon identifier. The availability of suitable iron plates determines the choice of the field cross section as 0.8 x 0.8 m. The spectrometer operates in a dc mode, but it is desirable occasionally to reverse the polarity from + 2T to -2T in order to average systematic errors.

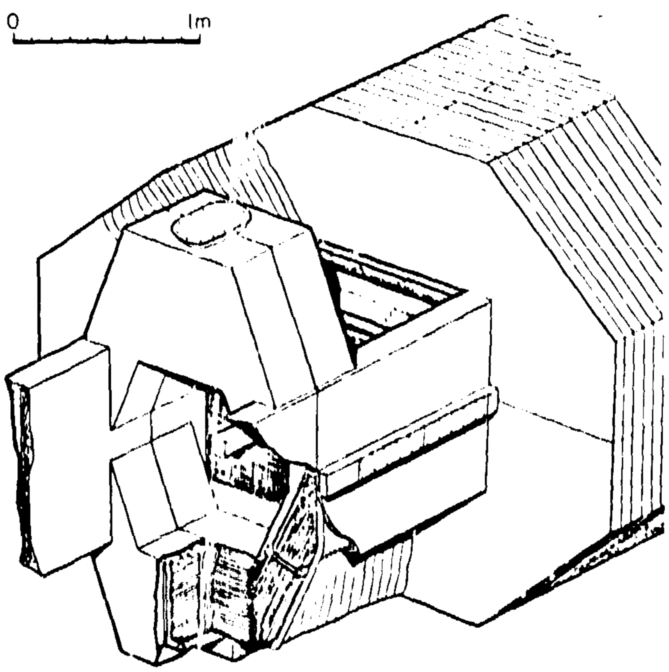

FIG. 1. CUTAWAY VIEW OF MAGNET; JUNCTION OF TWO 6 m UNITS

General requirement. The magnet must operate very reliably and be economical in construction and operation.

Design principles. A modular design with self-contained units of 6 m length allows off-site construction and transport of the magnets and does not give too many interruptions of the field by the saddle crossings, provided these use a minimum of longitudinal space. Each of ten 6 m units stores 9 MJ of magnetic energy at an operating current of 2 kA. Operation is below the full stability limit (i.e. minimum propagating zone is infinite, or cold-end recovery is possible). The windings are not potted, and indirect cooling of the superconductor by heat conduction through solid contact in vacuo avoids the necessity of an inner vacuum shell. An inner vacuum shell is a source of leaks impairing operation reliability and adds to the construction costs. Heat transport through solid contact has never been used in this manner; the missing experience must be replaced by careful verification tests. Should solid contact prove unreliable, an inner thin-walled vacuum shell filled with liquid or supercritical helium could be added without further alternations.

II. Construction

Assembly. The assembly of the coils is illustrated by Fig. 2 and described as follows.

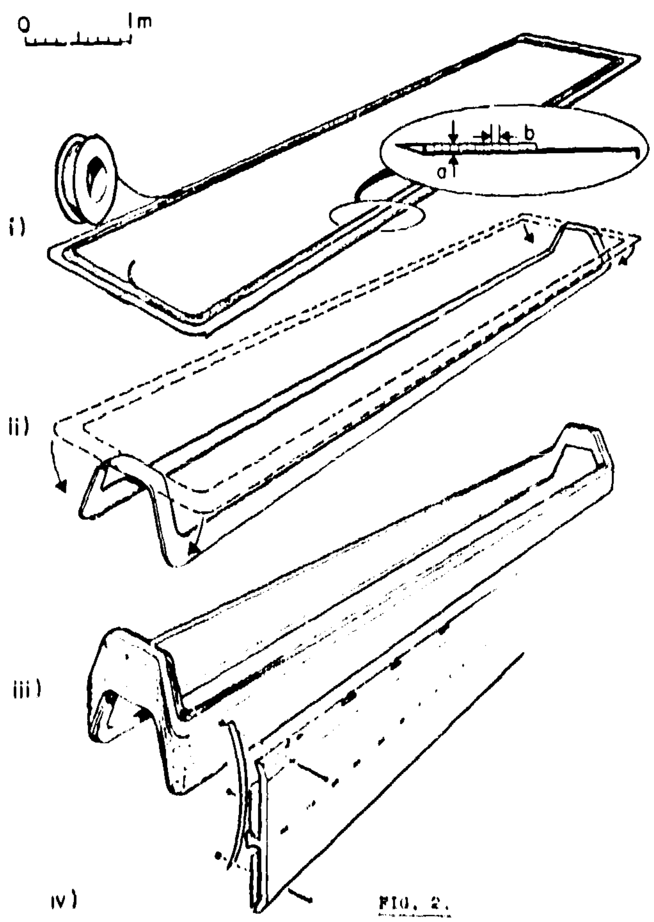

FIG. 2.
ASSEMBLY OF COILS

*Work performed under the auspices of the US Dept. of Energy.

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i) 22 turns of square cross section wire are wound as a flat pancake onto a window frame coil form. The coil form of high conductivity copper sheet (1.9 mm thick) is in two halves, connected by G-10 plates at the middle of the narrow ends, to avoid unnecessary eddy currents; copper cooling tubes of triangular profile are attached to the inner edges (see insert Fig. 2 and (b) in Fig. 3). Half the coils are wound clockwise, the other half anticlockwise.

ii) The coils are bent around a 10 cm radius to an angle of 70°. The angle is given by the exact dimensions of wire, insulation and coil form: $\cos\alpha = d/(4b)$, where $d^2 = 4[2b^2 + b(4b^2-a^2)^{1/2}]$; d is the vertical translation in the stack from one coil to the next, and a and b are dimensions indicated in Fig. 2.

iii) Alternate clock- and anticlockwise coils are stacked, using suitable insulation between coils, in addition to the wrapped insulation on the conductor. At the bottom and top of the stack are some coils with fewer turns, having the same inside dimensions (bottom) or outside dimensions (top, with round cooling tubes).

iv) The stacks are combined with the aluminum pressure plate (a) to which the outer set of triangular cooling tubes is attached (b). Clamps in the form of 1/4" thick G-10 strips are applied every 20 cm of the length of the pressure plate. The original curvature of the G-10 strips provides a slight pressure on the assembled coil and keeps the windings in place against gravity.

Electrical connections. The pancake coils are connected at the middle of one of the crossings. All the top and all the bottom saddle coils are connected in series between the units by means of an extra half turn located in the outermost pancake.

Cooling circuits. The inner and outer cooling tubes are connected in parallel so as to form 8 separate circuits for each 6 m unit. The corresponding sets are connected between all units in series. Two refrigerators each operate into 4 of the resulting 8 circuits. During cold operation the 4 circuits are in series. For cooldown all circuits run in parallel, the coolant flowing in the same direction, driving a cold front from the refrigerators to the warm end and returning through a separate line outside the cryostats.

Fifty layers of superinsulation at 20 layers/cm and a copper shield (c) at 70 - 100 K keep the heat leak at 4 K to about 6 W per 6 m unit. A further 5 W come through the warm supports (e).

III. Forces

Lorentz forces. At 2 T the total force of the windings onto the pressure plate is 1.9 MN per m length. Half the force is transmitted via cold tension members (g), located every 40 cm at top and bottom, to the opposite pressure plate. Tension members are of stainless steel, carrying 0.16 MN each; their T-shaped ends fit into slots of the pressure plate. The other half of the force is transmitted through center supports (3) to room temperature and via the iron yoke to the opposite supports. These supports, in sets of 36 cm length, each carrying 0.32 MN, consist of 8 equally spaced pressure posts of epoxy glass-fiber (G-10) connected by tension members of stainless steel sheet to pressure members of G-10 plates. The warm supports start operating at currents >280 A, when the center deformation of the pressure plates reaches 2 mm.

Gravity and iron attraction. The weight of the cold mass of 6 tons is to be carried by 7 stainless steel bands, spaced 80 cm, running from the bottom of the pressure plate to the top of the outer vacuum shell. Centering within the iron yokes is achieved by horizontal stainless steel wires (h) located in the same tubes as the cold tension members. The spring constant of all 60 wires is 50 nm/N (≈0.5 mm/ton), considered

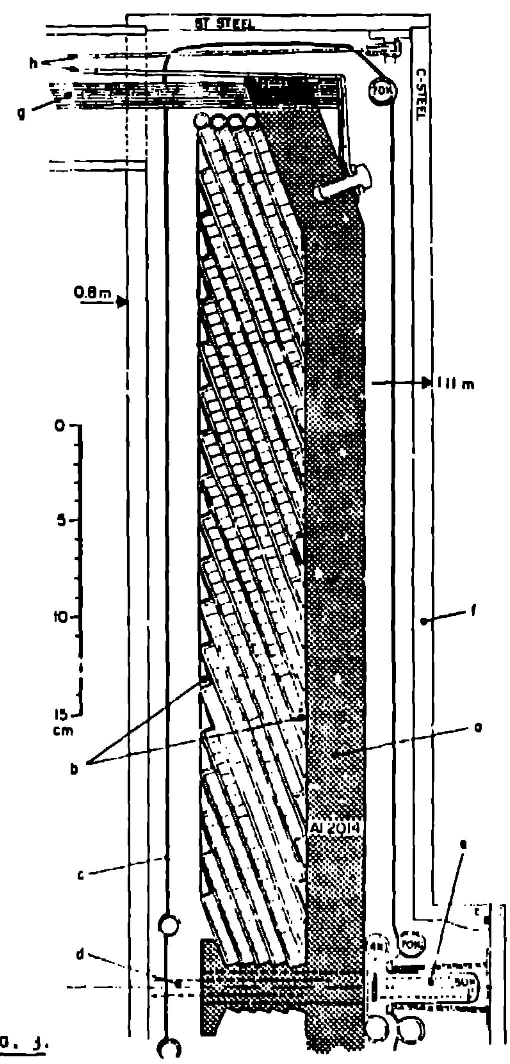

FIG. 3.
CROSS SECTION OF WINDING QUADRANT, INCLUDING CRYOSTAT

adequately stiff. Vertical upward movement is restrained by 7 wires from top of pressure plate to bottom of vacuum shell.

Vacuum forces. The walls of the vacuum shell (f) are too thin to support the bending moment of the vacuum forces unaided. Inner and outer wall are kept apart by warm G-10 pressure struts (d), every 40 cm, carrying 40 kN each. These struts have an H-profile to prevent buckling; situated between the main supports, in wide enough channels through the middle of the pressure plates, they do not touch any structure at 4 K.

IV. Stability of operation

Conductor. The conductor consists of 16 wires, each 0.635 mm diameter, with 360 NbTi filaments and a copper to superconductor ratio of 1.8, cabled around a square Cu core of 2 mm side. Two layers of copper wire, or a solid copper mantel, give a final size of 5.7 mm sides and an overall copper to superconductor ratio of 16:1. The whole is coated with pure indium. The insulation is 1 or 2 mil Kapton, Nomex, Teflon, Mylar: the choice depending on the best performance with regard to contact heat transfer (to be determined). Short sample current at 2 T and 4 K is 6 kA.

Stability of superconducting operation. There is global (or unconditional) stability if Joule heating in the normal state does not exceed local cooling into the coolant. At the limit of global stability the minimum

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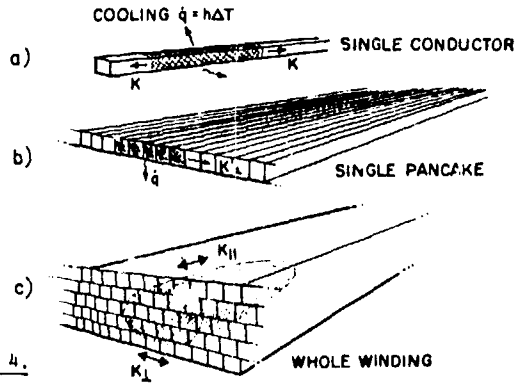

FIG. 4.

DIFFERENT GEOMETRIES OF MINIMUM PROPAGATING ZONES

recovery zone (MRZ) is zero [2] (also called limit of lateral recovery). At higher currents stability is still acceptable and recovery is possible provided a zone larger than the MRZ is kept superconducting. The limit is reached when both MRZ and minimum propagating zone (MPZ) are infinite; this is called full stability limit (also cold-end recovery limit). Beyond the full stability limit the MPZ is finite, and stability is only sufficient if disturbances are correspondingly small.

There are 3 geometries of MPZ to be considered, as illustrated in Fig. 4.

a) Single conductor. If it is in cooled contact on all four sides it has global stability to 2.2 kA and full stability to 2.9 kA. The stability parameters are[3]: $\xi_1 = 1.3$ and $\xi_o = 0.22$. However, if only one side is in cooled contact the global stability limit is at 1.26 kA and full stability at 1.7 kA and at 2 kA the MPZ is 17 cm long ($\xi_1 = 0.325$; $\xi_o = 0.055$). This means that single conductors such as current leads between coils must be cooled on more than one side; any one sided cooling over a distance longer than the MPZ cannot be tolerated.

b) Single pancake. Limit of global stability is at 1.7 kA, full stability at 2.16 kA ($\xi_1 = 0.68$; $\xi_o = 0.12$). This case reflects the stability of the whole coil under normal operating conditions.

c) Cooling into whole winding (coolant not active). The MPZ is always finite.[4] At 2 kA the MPZ, cigar-shaped, is 34 cm long and has a central diameter of 1 cm, i.e. it is equivalent to two neighboring conductors being normal for a length of 21 cm. The energy required to produce such a normal zone is 0.15 J. This case represents the situation after a total cooling breakdown.

About disturbances. The windings are not potted. They can adjust to elastic deformation while the coil is being energized. The risk of large movement at high current is small.

Heat transport. The thermal conductivity of the conductor will be $k_{\parallel} = k_{Cu} = 10$ W/cm K. The insulation has $k_{ins} = 1$ mW/cm K and thickness $d_{ins} = 0.1$ mm. The heat transport through the insulation into the copper coil form is represented by a heat transfer coefficient $h_{ins} = k/d = 0.1$ W/cm²K. If heat transport from turn to turn is considered, an effective thermal conductivity $k_{\perp} = k_{ins}(d_{cond} + d_{ins})/d_{ins} = 50$ mW/cm K is active. Above stability limits are calculated by assuming that 20% of surfaces are in good contact with each other and without thermal contact resistance; the other 80% do not conduct any heat at all. Thus, the values used above for thermal conduction are $h_{ins} = 20$ mW/cm²K and $k_{\perp} = 10$ mW/cm K.

Proposed correlations for heat transfer by contact between solids in vacuo suggest[5]:

$$C\, a / A\, k \approx W / A\, M$$

with C thermal conductance (W/K); a surface quality, e.g. surface roughness (m) / mean surface slope (radian); W load (N); A nominal contact area (m²); k thermal conductivity (W/m K), harmonic mean between two different materials; M = 3 x yield strength (Pa). Such a correlation produces very nearly the same result as the above 20% assumption. Pure indium coating is expected to improve heat contact because of its low yield strength. Experimental determination is necessary.

V. Cost estimate and further detail

The cost for a 6 m unit, including cryostat, is estimated as 340 k\$. This includes conductor cost of 150 k\$, other material costs of 15 k\$, labor 95 k\$, engineering and contingencies 80 k\$. A comparison with 1979 prices[6] of coils of similar geometry is given in Fig. 5 where the weight of a large number of other coils is also entered, demonstrating the well known trend ($\approx E^{-0.4}$) of increased efficiency towards higher energies.[7]

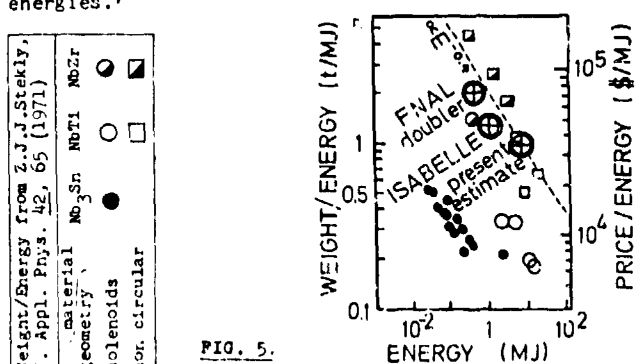

FIG. 5.

COMPARISON OF SEVERAL COILS
price scale applies only to ⊕; weight scale does not apply to Doubler and Isabelle dipoles

Further detail on the above topics and also on eddy current and cooling losses are found in ref. 1 and in the following table.

TABLE OF DATA (for 6m unit, unless specified otherwise)

filament critical current density (2T)	330 kA/cm²
operating current	2 kA
turns	796
inductance	4.32 H
average conductor current density	6.15 kA/cm²
winding + pressure plate cross section	812 cm²
overall current density	2 kA/cm²
Quench current, estimated	2.5 kA
Refrigerator power consumption for all 10 units, approx.	
dc operation (no eddy current losses)	65 kW
maintaining 4 K (cryostat loss only)	38 kW
length of cooling circuit (all 10 units)	82.5 m
flow cross section, each circuit	7 cm²
minimum coolant flow, total	6 g/s
flow speed, as gas: 50 cm/s; as liquid:	7 cm/s
helium inventory	45 l
thermal contraction, RT to 4K	2 cm
cold mass	6200 kg
outer vacuum shell	2600 kg

VI. Conclusion

A conceptual design study of a 90 MJ magnet for use in high energy physics experiments has been presented. Modular construction simplifies manufacturing. Indirect cooling by heat transfer through solid contact requires verification studies. Chief advantage of this cooling method is a simpler cryostat; penalty is a higher superconductor price. The operating current, at 33% of short sample critical current, is slightly below the full stability limit.

Acknowledgement

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